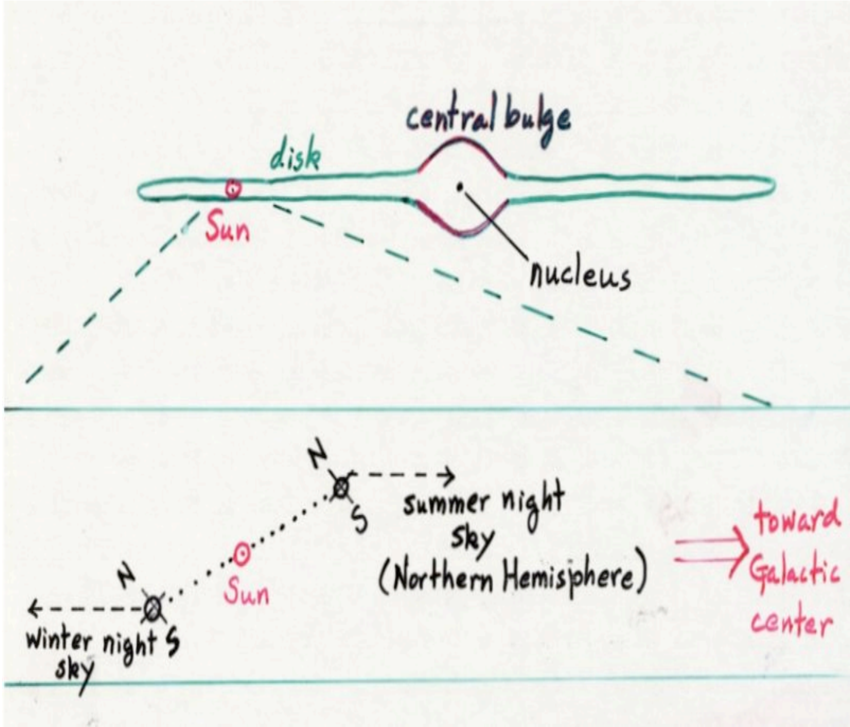
Lecture 19

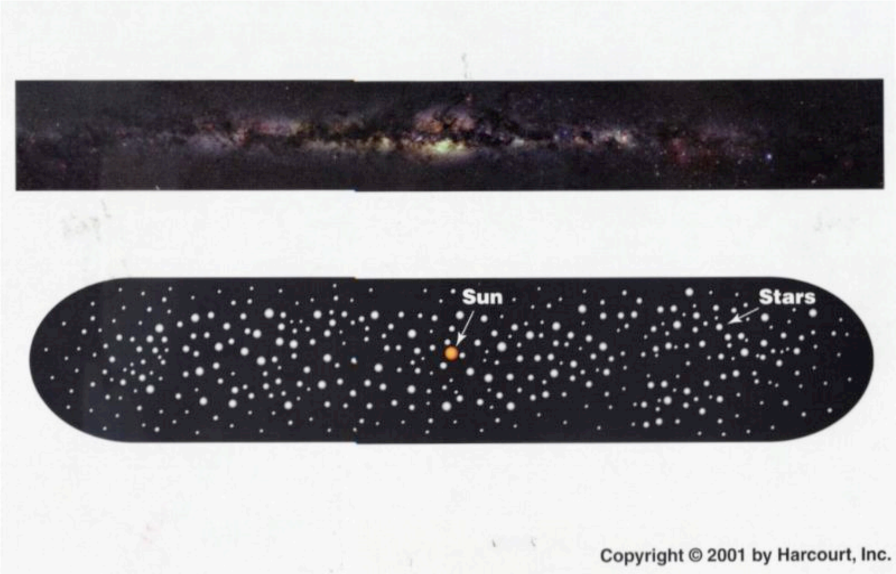
The Milky Way Galaxy

Outline of Lecture 19

- Discovery of the large size of the Galaxy and our location in it.
- The observable Galaxy consists of a disk, central bulge, and halo:
  - Contents and motion of various components
  - Differential rotation of the disk and the implication for the enclosed mass
- The light distribution and the evidence for *dark matter*.

The Milky Way Galaxy Consists of Innumerable Stars and Gas and Dust Clouds





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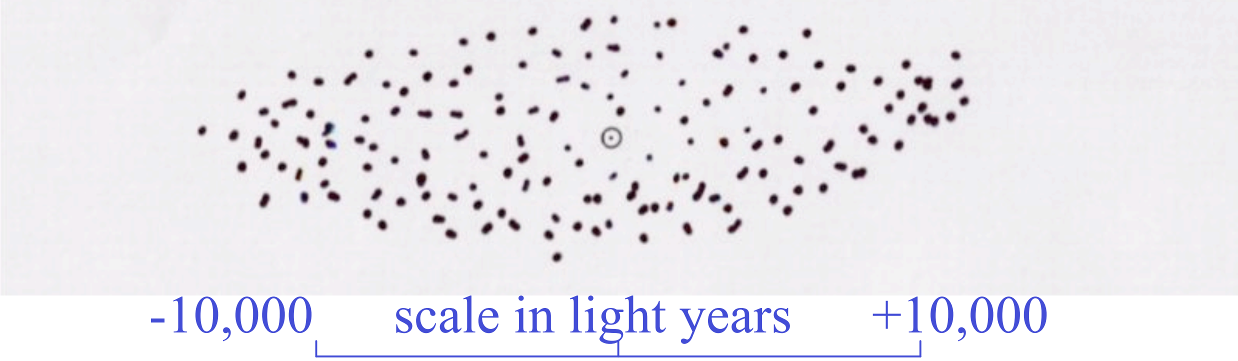
Presence of dust in the plane of the disk obscures an optical view of the distant Milky Way, deluding early workers like Jacobus Kapteyn into thinking that the distribution of stars thins out in every direction from the location of the solar system.

Discovery of the Galaxy

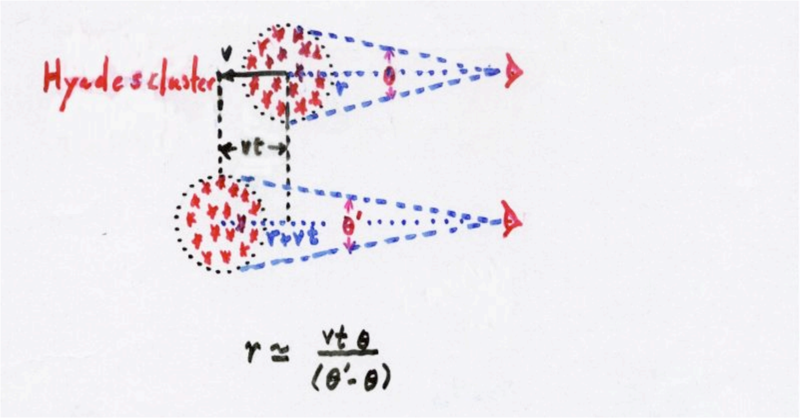
- Greeks: Milky Way as a river of milk (“galaxy” is derived from the Greek word for milk.) Chinese: river of silver (“yin he”).
- Galileo: Milky Way as innumerable stars.
- Kapteyn (1851-1922): Milky Way as stellar universe.

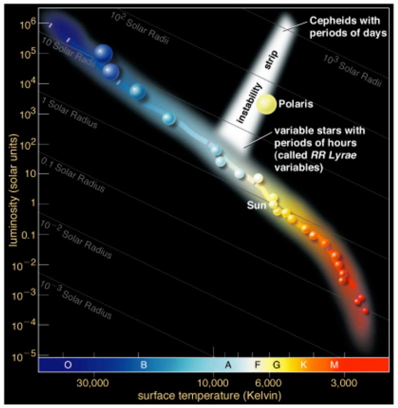


- Henrietta Levitt (1868-1921): Period-Luminosity relationship of Cepheids – distance to Magellanic Clouds.
- Harlow Shapley (1885-1972): Shape and size of system of globular clusters – distance to center of Galaxy.

Moving Cluster Method and Cepheid Variables

- From moving cluster method, obtain distance to Hyades star cluster as 430 lt yr.
- From main-sequence fitting, obtain distances of other clusters relative to Hyades (Lecture 17).
- In open clusters with distances, find pulsating stars called Cepheids – discover they have a period-luminosity relationship.
- With calibrated absolute brightnesses, Cepheids can be used as “standard candle.”
- Modern space astrometry promises to yield parallaxes accurate to a few microarcseconds. Thus, astronomers will soon be able to obtain trignometric distances out to a million light-years distance, i.e., to the nearest galaxies directly without the problem of intermediate calibrators.





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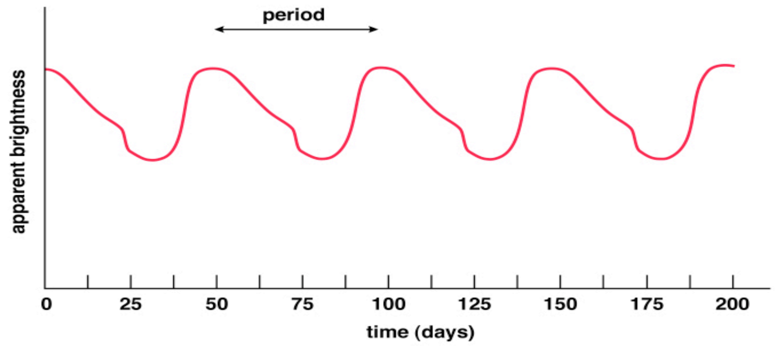
Location of Cepheids in “instability strip” of cluster H-R diagram.

Cepheids Are Pulsating Stars Which Can Be Used as Distance Indicators

- Cepheids vary in light output because they pulsate in and out, mostly in a “breathing mode.”
- As star becomes larger or smaller, it has more or less radiating area, which also correlates with variation of color of star and the Doppler variability of its spectral lines.
- The bigger is the average size of a Cepheid, the larger is its average luminosity *L* and the longer is its pulsation period (time interval to “breathe” in and out).
- In other words, Cepheids have a period-luminosity relationship that can be calibrated if we have their distances.
- Conversely, once we’ve calibrated the period-luminosity relationship, we can obtain the luminosity *L* of a Cepheid by measuring its period.
- From a measurement of its average apparent brightness *f*, we can then deduce the distance of the Cepheid from $r = (L/4\pi f)^{1/2}$.



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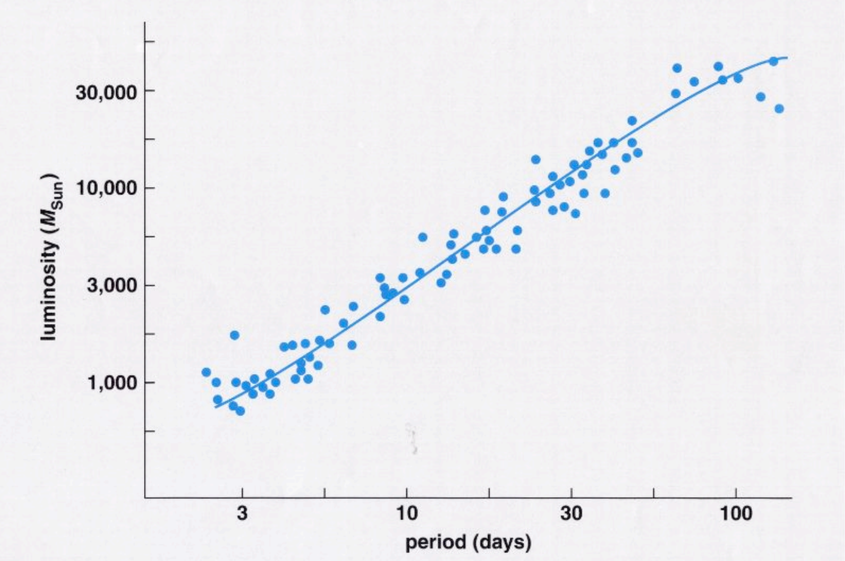

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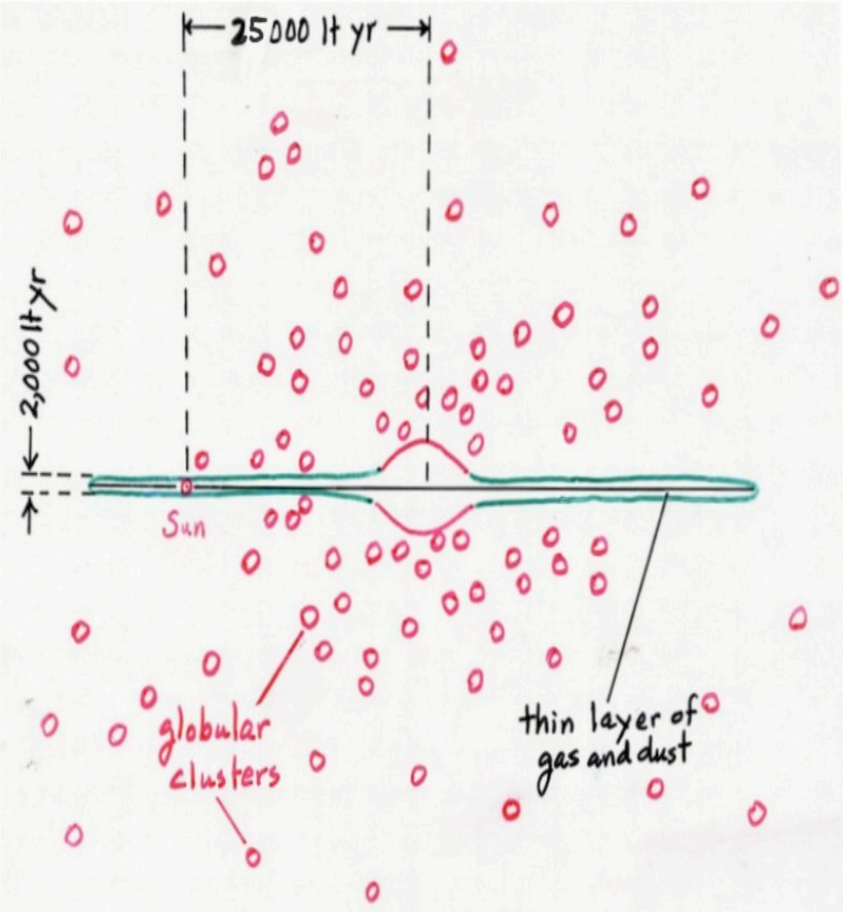
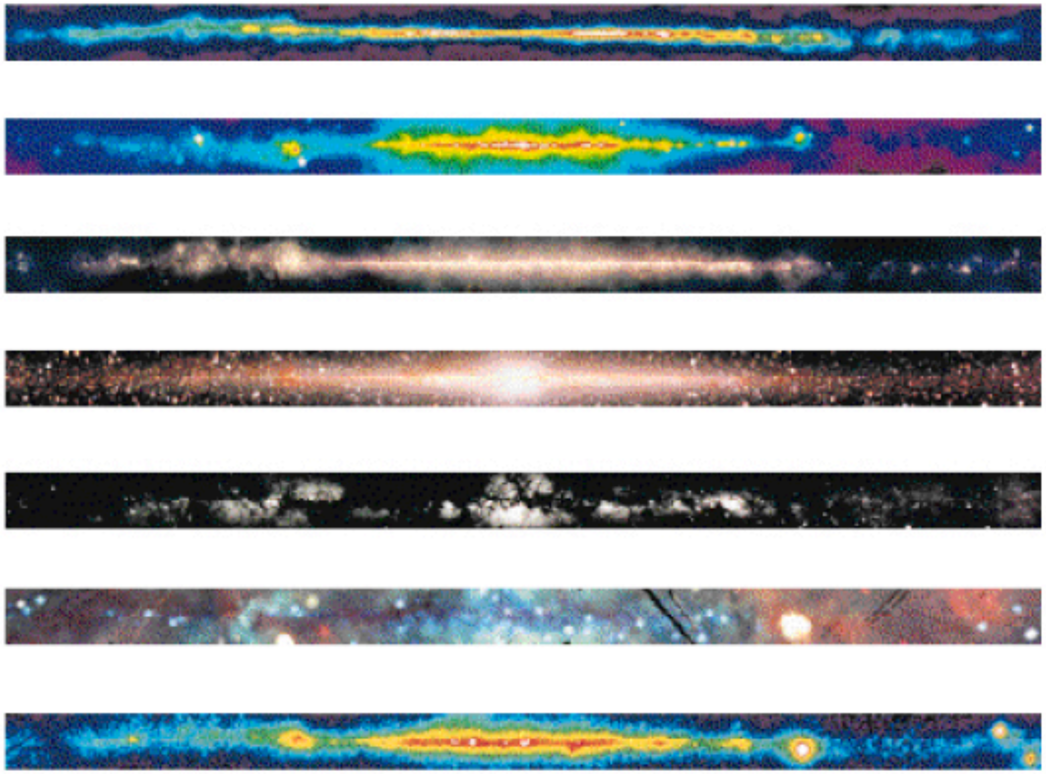
Modern View of the Galaxy

- Shapley measures distance to globular clusters in halo of Galaxy applying Henrietta Levitt's period-luminosity relationship to RR Lyrae variables in instability strip on Horizontal Branch.
- Shapley discovers that globular clusters form a spherical distribution with center at a large distance from location of Sun.
- If he assumes that this center is the center of the Galaxy as a whole, the Sun lies at a distance of 25,000 lt-yr (modern value) from the Galactic Center.



Milky Way in Different Wave Bands (extra material)



(a) 21-cm radio emission from atomic hydrogen gas.

(b) Radio emission from carbon monoxide reveals molecular clouds.

(c) Infrared (60–100 μm) emission from interstellar dust.

(d) Infrared (1–4 μm) emission from stars that penetrates most interstellar material.

(e) Visible light emitted by stars is scattered and absorbed by dust.

(f) X-ray emission from hot gas bubbles (diffuse blobs) and X-ray binaries (pointlike sources).

(g) Gamma-ray emission from collisions of cosmic rays with atomic nuclei in interstellar clouds.

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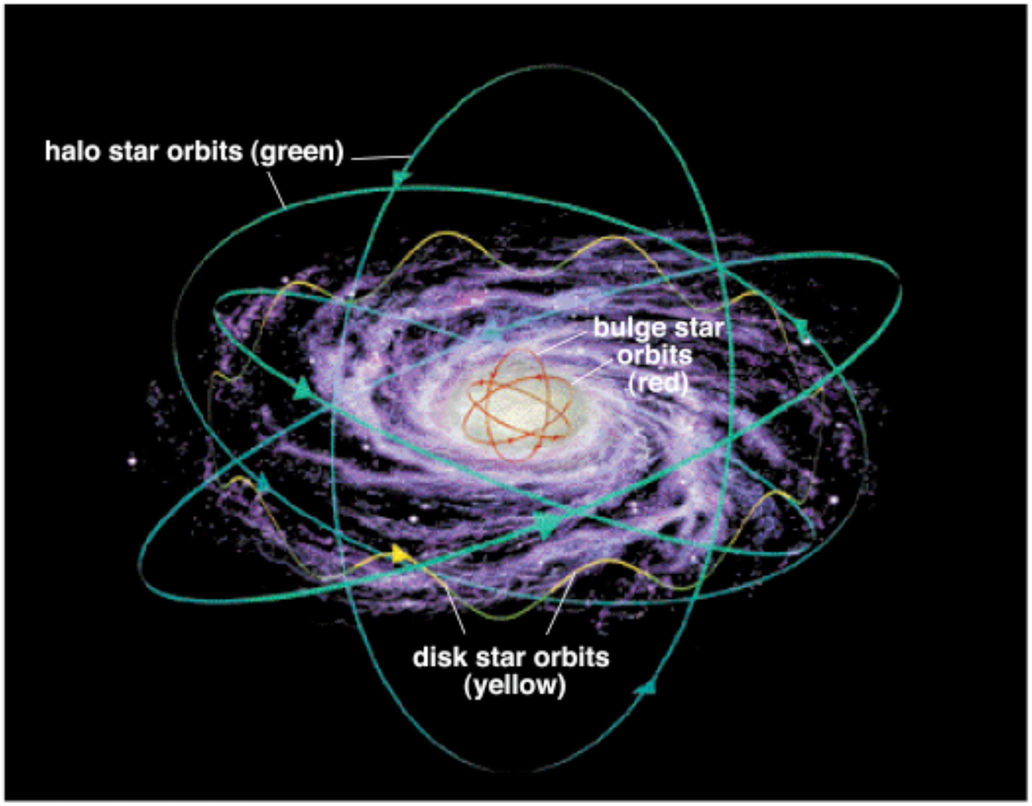
Orbits of Stars in the Galaxy

Yellow orbit confines disk star to small-amplitude oscillations about the disk's mid-plane while circling center. Red orbits show bulge stars to swarm Galactic center like bees around a hive. Green orbits show halo stars to soar like high-flying jet fighters throughout the whole Galaxy.

Orbit diagrams are schematic here. In actuality, none of the orbits close on themselves nor lie in a single plane because the mass distribution is neither concentrated at a single point in the center nor spread uniformly in a large sphere around it.



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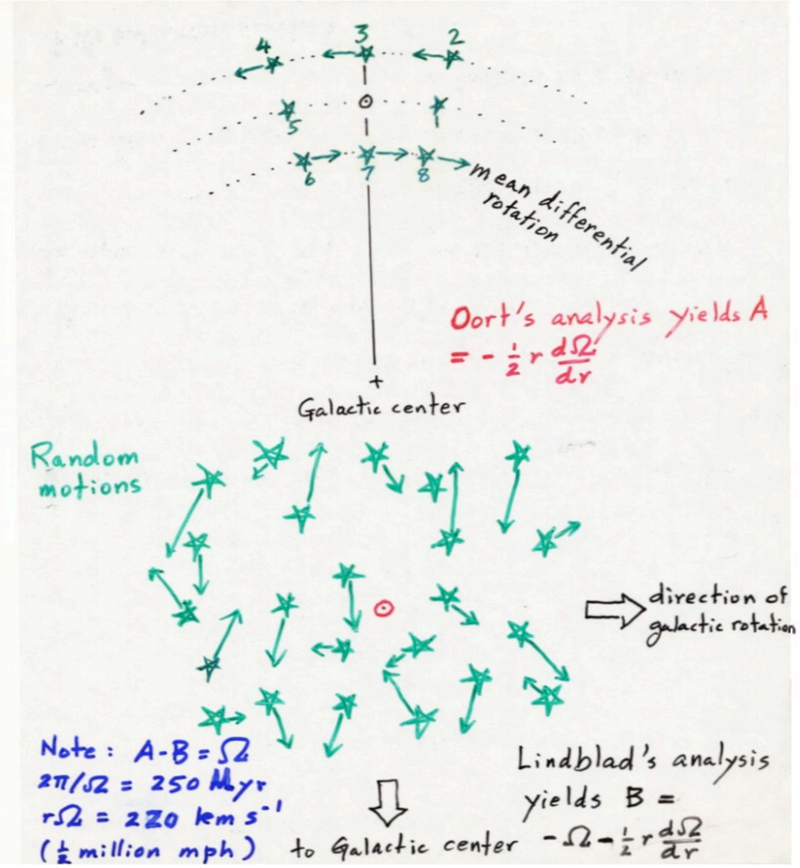
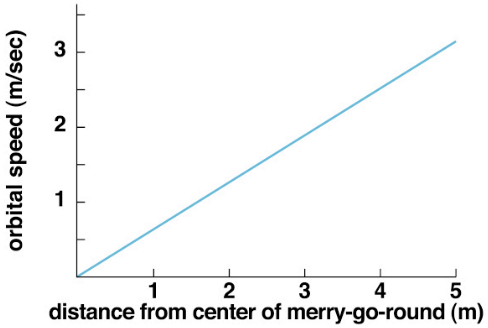
Analysis of Local Differential Rotation by Oort (1900-1992) & Lindblad (1895-1965)



- Lindblad constructs an "epicyclic theory" of disk-star orbits that motivated the description we gave in Chapter 6 for planetary orbits.
- Lindblad shows that the ratio of the random velocities of disk stars in the radial and tangential directions (which is empically measurable) depends on a combination of Oort's *A* and *B*. Oort's analysis yields *A*; Lindblad's then gives *B*.
- We now obtain the angular velocity of rotation $A - B = \Omega$ of the Sun around the Galactic center (GC).
- Period of the Sun's rotation about the GC = $2\pi/\Omega$= 220 million yr.
- Since the Sun's distance from the GC is r = 25,000 lt years, the Sun's circular velocity = $r\Omega$= 220 km/s

Galaxy is a very big place, because even flying at half a million miles per hour, the Sun takes 220 million years to circle the Milky Way once!

Galaxy Has a Flat Rotation Curve



(a)

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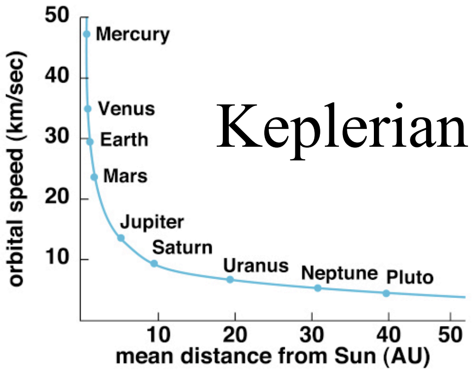
Solid body rotation



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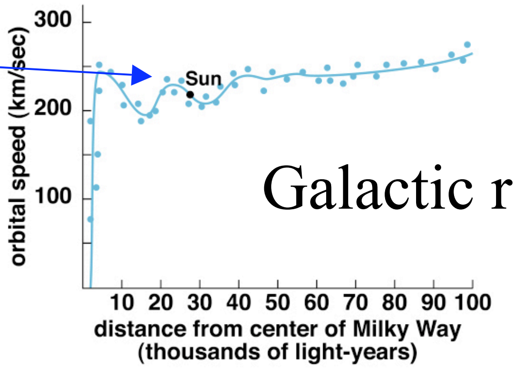
Keplerian rotation

Global rotation curve in Galaxy is

(a) obtained from radio astronomy

- 21 cm line from spin-flip of electron (relative to proton) in ground electronic state of atomic H, and
- millimeter-wave transitions of quantized rotational states of the diatomic molecule CO;

(b) flat in its outer parts, i.e., speed neither increases with distance (as in solid-body rotation), not decreases (as in Keplerian rotation of planets about Sun).



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Galactic rotation

Differential rotation

Estimate of Mass Interior to *r*

- If the distribution of mass (unlike that of light) were spherical, then we can define *M(r)* = mass interior to a sphere of radius *r* from the center of the Galaxy.
- Star or gas cloud at radius *r* traveling in a circle with speed v has an associated acceleration *a* (according to Huygens) of

$$a = \frac{\mathrm{v}^2}{r}.$$

- This acceleration must be produced by a gravitational field *g*, which (according to Newton) is given for a spherical mass distribution by

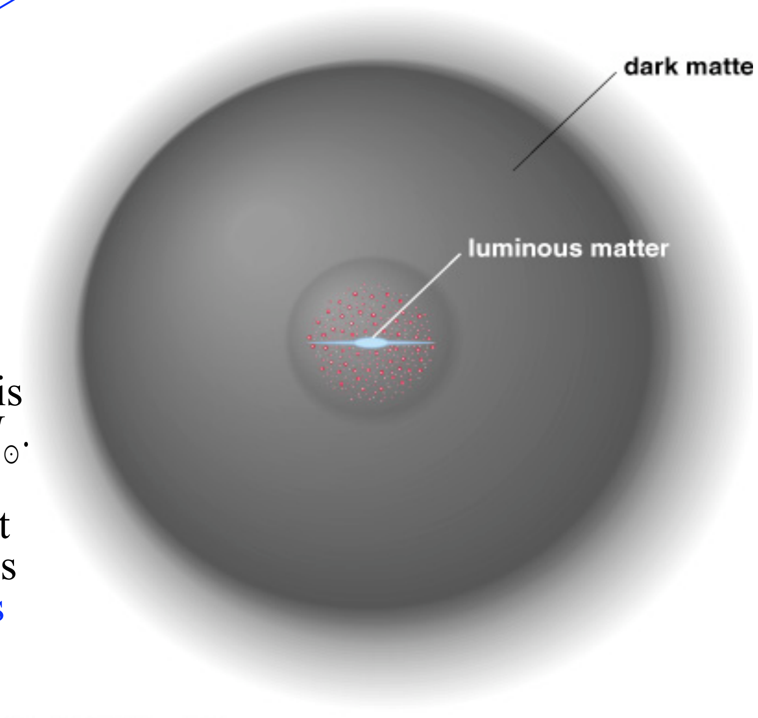
$$g = \frac{GM(r)}{r^2}.$$

- Setting *a* = *g*, we get

$$M(r) = \frac{r\mathrm{v}^2}{G}.$$

- For v = 220 km/s at r = 25,000 ly, we get $M(r) = 0.8\times10^{11} M_\odot$. There are about 100 billion stars in the Milky Way if half of this mass is associated with stars and the average star is about $0.4M_\odot$.
- For v = 250 km/s at r = 100,000 ly, we get $M(r) = 4\times10^{11} M_\odot$. Most of this matter is dark matter since there is little starlight at such distances. We now believe that the dark matter in galaxies must be roughly 5-6 times greater than the amount of luminous matter. We have no definitive idea what is the physical nature of this dark matter, but it is probably distributed roughly spherically in a large halo surrounding the galaxy it hosts.

This derivation is algebraically identical to the one we gave for the mass of the Sun when we know the speed and distance of the Earth from the Sun (Lecture 5).



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